DETERMINATION AND APPLICATIONS OF
THREE-PHASE POWER FACTOR

INVENTORS

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BACKGROUND OF THE INVENTION

This disclosed embodiment relates to a three-phase power system such as, for example, a large commercial chiller. More particularly, this disclosed embodiment relates to determining three-phase power factor of a three-phase power system under load and using this three-phase power factor to protect the

5   system from damage caused by such phenomenon as momentary power loss conditions.

In large commercial chillers, three-phase is the power of choice. Three-phase power systems consist of three alternating sources nominally spaced 120 degrees with respect to each other. The spatial separation of these

10   sources set up a cyclic pattern that, when applied to a specific load, sets up a rotating magnetic field. This rotating magnetic field is ideal for allowing motors to turn successfully by converting electrical energy to mechanical energy. In commercial chillers, this mechanical energy is used to turn a refrigerant compressor, one of the critical stages in the refrigerant cycle.

15   Although disclosed in terms of a commercial chiller, the present invention is intended to encompass the calculation of power factor in other applications.

Another type of power source is single-phase. In a single-phase power system, power is delivered to a load via a single alternating source. Even though the source is alternating, it is alternating within itself only and has no

20   point of reference upon which a rotating magnetic field may result. If single-

phase power is used to energize motors, a rotating magnetic field needs to be artificially created locally to the motor, usually with a capacitor. Single-phase motors tend to be small in horsepower and have a large ratio of line current to horsepower. Three-phase power has the added advantage of delivering its

5   energy through three sources instead of just one, resulting in smaller wire gauges to deliver the same amount of energy.

Working with three-phase systems presents issues not found in single-phase systems. In single-phase systems, there is a single source voltage and a single current that result when this source voltage is applied to a load. From

10   measuring these two parameters, power factor can be calculated as:

$$\text{Power Factor} = \cos \Phi$$

Where Φ is the phase angle in which the current lags the voltage.

In working with three-phase systems, the determination of power factor is not a straight-forward calculation involving single entities of current and

15   voltage phase angle. In three-phase systems, three sets of voltages and currents are all interacting with each other. If the three-phase system is symmetrical, that is, if all voltage sources are at exactly the same level and are exactly 120 degrees spatially apart, and the load each source sees is exactly the same, then the angle between the current and voltage of any particular phase of

20   the load may be used to determine the three-phase power factor as:

$$\text{Three-Phase Power Factor} = \cos \Phi_p$$

Where Φ_p is the phase angle in which the current lags the voltage of the same configuration, i.e. both current and voltage measurements are taken in-the-delta of the motor.

However, sources of three-phase power systems are rarely balanced (i.e. the levels of the line-to-line voltages are equal, $V_{ab}=V_{bc}=V_{ca,}$ as seen by the load) nor is the load itself balanced between the three phases. There is no one angle between a voltage and a current that will indicate true three-phase

5   power factor. In addition, Φ_p is the angle the current lags the voltage for currents and voltages measured in the same configuration. These are, for example, the currents and voltages across the load phase itself (i.e. delta currents and voltages). They also could be the currents and voltages of the source lines (i.e. wye currents and voltages). Typical control modules measure

10   line currents and line-to-line voltages which, since they are not in the same configuration, have a 30 degree offset in the phase angle even if the load is a pure resistor. Here, the true three-phase power factor is unity (the true power factor angle is zero).

Previous designs have attempted to determine three-phase power factor

15   by using one line current and one line-to-line voltage, accounting for the 30 degree difference. This method is only valid for ideally balanced sources and loads, which is rare in reality. The advantage of this method is that it is simple to implement and takes very little computing resources of a processor, memory, and processing power. An inexpensive processor could be used with

20   this method. However, errors in power factor can be as great as 20% under normal unbalanced conditions. This large error gives the customer a false reading regarding what power factor the chiller is performing at, and limits other functions using power factor in their calculations. These other functions include determination of power consumption, surge conditions, and

25   momentary power loss conditions.

True three-phase power factor calculations that are insensitive to the balance of load and source have been accomplished using a high-end processor capable of performing multiple trigonometric functions and digital signal processing. This processor is relatively expensive.

5   Momentary power losses (MPLs) are short durations of interruptions of the power being supplied to a load such as a motor. These interruptions may be the complete loss of all three phases of incoming power, the loss of one or two phases, or a dip in one, two, or all three phases. These interruptions may be very destructive to the rotating devices being powered. The devices include

10   the motors themselves and/or their loads such as, for example, compressors. The destructiveness of the interruption is dependent on the type of motor and load and the nature and duration of the interruption. For small inertia loads, the motor/load decelerates and accelerates with the interruption with little impact on the reliability of the electromechanical system. For larger inertia

15   motor/loads, the reclosure torques and currents are of a very large level for a longer period of time and impact the reliability of the motor and load. Transient currents may be as high as twelve times full load amps and transient torques may be as high as twelve times full load torque.

Reclosing into momentary power losses may result in large transient

20   torques that could damage motor stator windings, motor shafts, impeller or shaft keyways, the impellers themselves, starter contactors, and branch circuit components. Momentary power losses may also cause the electronic controls to drop out unexpectedly and keep the system off until an operator gets involved. This could mean significant downtime for the system, resulting in a

25   dissatisfied customer.

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Momentary power losses may be caused by fault clearing devices being activated as the result of the forces of nature such as lighting strikes or animals coming into contact with the power lines. These interruptions may also be caused by power switching gear where a section of the power supply is

5   moved from one power source to another.

Trying to detect momentary power loss and/or surges based on a single phase voltage and current of a three-phase power system can result in falsely detecting a momentary power loss condition or not detecting a true momentary power loss condition at all.

10   U.S. Patent 4,751,653 to Junk et al. is directed to a microprocessor based fault detector for identifying phase reversal, phase loss, and power loss in three-phase circuits. U.S. Patent 4,802,053 to Wojtak et al. is directed to a system for sensing the phase of a three-phase AC system and detecting phase reversal, under voltage, and phase unbalance. U.S. Patent 5,058,031 to

15   Swanson et al. is directed to a method of protecting the compressor motor of a refrigeration system using a multi-phase AC power source. U.S. Patent 5,184,063 to Eisenhauer is directed to a three-phase reversal detection and correction system. U.S. Patent 5,200,682 to Kim et al. is directed to motor current phase delay compensating method and apparatus.

20   An approach to generating three-phase power factor directly and simply with an inexpensive set up and without having to convert between wye and delta configurations and without having to employ trigonometric calculations or having to measure phase, is desired. It is also desired to use three-phase power factor to protect three-phase power systems and their loads

25   from damage.

BRIEF SUMMARY OF THE INVENTION

One aspect of the disclosed embodiment is a three-phase power system capable of sourcing power to a motor that drives a load such as, for example, the compressor of a chiller. The system sources three-phase power to a motor by applying three lines of voltage and current to the motor. Apparent power from a source has components of real power, reactive power, and distortion power. Real power is the power supplied by the source and dissipated by the load. Reactive power is a measure of the energy exchanged between the source and the load without being dissipated. Distortion power is that portion of the apparent power that cannot be used by the load due to distortions in the waveforms of the voltage and current. Power factor is the ratio of real power to apparent power and is, therefore, that fraction of the apparent power actually dissipated by the load. Power factor is also expressed as the cosine of the phase angle by which the current lags the voltage. In a three-phase power system, all three voltages and currents must be considered when determining a meaningful power factor.

Apparatus for determining instantaneous three-phase power factor and true three-phase power factor is provided. "True" means representative of the effective load the power is being sourced to over a line cycle. "Instantaneous" means representative of the load the power is being sourced to at a specific point in time. This apparatus includes a processor that monitors voltage levels and current levels from the source power lines of the three-phase power system. These voltage and current levels are sampled at a pre-determined rate and are used to calculate the power factors.

Another aspect of the disclosed embodiment is an apparatus for detecting momentary power loss conditions and other conditions with respect to normal operation. This apparatus includes the processor described above to process the three-phase power factor in order to detect these conditions. This allows the processor to react to the system to prevent damage to the motor and/or load of the system by these conditions.

A method for determining instantaneous three-phase power factor and true three-phase power factor is provided. "True" means representative of the effective load the power is being sourced to over a line cycle. "Instantaneous" means representative of the load the power is being sourced to at a specific point in time. This method includes monitoring voltage levels and current levels from the source power lines of the three-phase power system. These voltage and current levels are sampled at a pre-determined rate and are used to calculate the power factors.

Another aspect of the disclosed embodiment is a method for detecting momentary power loss conditions and other conditions with respect to normal operation. This method includes processing the three-phase power factors in order to detect these conditions. The method is able to react to the detection of these conditions to prevent damage to the motor and/or load of the system by these conditions.

The present invention provides a method of calculating power factor. The method comprises the steps of: determining three sets of currents respectively associated with three motor phases; determining three sets of voltages respectively associated with three motor phases; calculating current phasors and voltage phasors from the sets of currents and sets of voltages; and determining an instantaneous power factor from the calculated current and voltage phasors.

The present invention further provides an arrangement for calculating power factor. The arrangement comprises apparatus determining the magnitude of three sets of currents respectively associated with three motor phases; apparatus determining the magnitude of three sets of voltages

5   respectively associated with three motor phases; apparatus calculating current phasors and voltage phasors from the sets of currents and sets of voltages; and apparatus determining an instantaneous power factor from the calculated current and voltage phasors.

By using the foregoing techniques, a simple, cost-effective approach to

10   monitor the lines of a three-phase power system, calculate three-phase power factors, detect conditions which can cause damage to the system, and prevent such damage from occurring is achieved.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic block diagram of a three-phase power system made in accordance with the disclosed embodiment, particularly showing the

15   processor that samples the voltage and current levels.

Figure 2 is a diagram of the traditional wye and delta configurations that the three-phase source and load can have in the three-phase power system of Figure 1.

Figure 3 is a modified schematic block diagram of the three-phase

20   power system shown in Figure 1, particularly illustrating certain aspects of the processor including the digitization of the voltage and current levels and algorithms of the disclosed embodiment.

Figure 4 is a flowchart of the momentary power loss algorithm illustrated in Figure 3.

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DETAILED DESCRIPTION OF THE INVENTION

The features of one embodiment enable a simple, low cost apparatus and method for determining three-phase power factor in a three-phase power system under load. This power factor is then used to detect momentary power loss conditions and other adverse conditions to allow action to be taken in order to protect the motor and load of the three-phase power system from damage when these conditions occur. This is accomplished by using a low-cost processor to sample voltage and current levels from the source lines of the three-phase power system and to perform subsequent calculations of power factor and detection of adverse conditions from these voltage and current levels.

Figure 1 is a schematic block diagram of a three-phase power system 10 made in accordance with the disclosed embodiment. A three-phase source 20 provides three-phase power over source lines 30, 40, and 50 to a three-phase motor 60 that drives a load 70. A processor 80 is configured to sample voltage levels and current levels from the source lines 30, 40, and 50.

Figure 2 shows the traditional delta configuration 90 and wye configuration 100 of how the source 20 and motor 60 can be configured in a three-phase power system 10. The disclosed embodiment is independent of these configurations and the various combinations thereof.

Figure 3 illustrates more detail of the disclosed embodiment including digitizers 110 and 120 of processor 80 for digitizing the voltage and current levels, and motor contactors 130 for connecting and disconnecting the motor 60 from the source lines 30, 40, and 50. The processor 80 also employs several software algorithms. These comprise a three-phase power factor algorithm 140, a momentary power loss (MPL) algorithm 150, and a surge algorithm 160.

The three-phase source 20 is electrically connected to the motor contactors 130 over the source lines 30, 40, and 50. The motor contactors 130 are electrically connected to the three-phase motor 60 over a contactor/motor interface 170 to provide three-phase power to the motor 60. The voltage digitizer 110 in the processor 80 is electrically connected to the source lines 30, 40, and 50 over voltage sampling interfaces 180, 190, and 200 to sample voltage levels. The current digitizer 120 in the processor 80 is electrically connected to the source lines 30, 40, and 50 over current sampling interfaces 210, 220, and 230 to sample current levels. The processor 80 is electrically connected to the motor contactors 130 through a processor/contactor interface 240.

To determine a value of three-phase power factor, the positive and negative levels of voltages and currents are measured from the source lines 30, 40, and 50 by the processor 80, maintaining the positive and negative signs of the measured levels. The measurements may be taken in various combinations of phase and/or line voltage levels and current levels (see Figure 2) such as:

first combination:	Vab, Vbc, Vca, Ia, Ib, Ic
second combination:	Va, Vb, Vc, Iab, Ibc, Ica
third combination:	Vab, Vbc, Vca, Iab, Ibc, Ica
fourth combination:	Va, Vb, Vc, Ia, Ib, Ic

where a, b, and c refer to the three source lines 30, 40, and 50 respectively. For example, Va is the phase voltage level on source line a with respect to a voltage reference. Vab is the line voltage levels between source lines a and b.

The three voltage levels and three current levels are sampled and digitized by the processor 80 and used to calculate values of a voltage phasor and values of a current phasor based on the expected geometric arrangement of the magnetic fields produced by the three phases. The values of real components (Vr and Ir) and the values of imaginary components (Vi and Ii) of the phasors are given by the following equations based on the 120° separation of the three phases:

If Vab, Vbc, and Vca are used:

$$Vr = 3^{0.5}*0.5*Vbc \quad \text{and} \quad Vi = 0.5*(Vab-Vca)$$

If Va, Vb, and Vc are used:

$$Vr = 3^{0.5}*0.5*(Vb-Vc) \text{ and} \quad Vi = Va-0.5*(Vb+Vc)$$

If Ia, Ib, and Ic are used :

$$Ir = 3^{0.5}*(Ib-Ic)/3 \quad \text{and} \quad Ii = Ia$$

If Iab, Ibc, and Ica are used:

$$Ir = 3^{0.5}*(2*Ibc-Ica-Iab)/3 \quad \text{and} \quad Ii = Iab-Ica$$

These equations for Vr, Vi, Ir, and Ii assume the six levels are sampled simultaneously by the processor 80. If the six levels are not sampled simultaneously, the above equations must be modified to compensate for the resulting phase angle discrepancies. Also, for the line-to-line voltage levels and the line current levels, only any two need to be sampled by the processor 80. The third can be calculated from the other two by the processor 80. Additionally, a person of ordinary skill in the art will recognize that other equations may be used by adjusting the correspondence between phasor coordinates and three-phase coordinates.

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The value of instantaneous power factor is calculated by the processor 80 using the algorithm 140 as

instantaneous power factor = cos Φ

where Φ is the spatial or geometric angle by which the current lags the voltage or the value of instantaneous power factor is calculated as

instantaneous power factor = cos(angle of the voltage phasor – angle of the current phasor).

$$= \cos(\theta_V - \theta_I)$$

In other words,

power factor = power/apparent power

$$power = \vec{V} \cdot \vec{I}$$

$$apparent\ power = |\vec{V}| \cdot |\vec{I}|$$

$$= (V_r^2 + V_i^2)^{0.5} \cdot (I_r^2 + I_i^2)^{0.5}$$

$$= [V_r^2 + V_i^2) \cdot (I_r^I + I_i^2)]^{0.5}$$

The calculation of power is well-known by various calculations but the present invention's calculation of apparent power is unique.

Since,

$$\cos(\theta_V - \theta_I) = \cos(\theta_V) \cdot \cos(\theta_I) + \sin(\theta_V) \cdot \sin(\theta_I)$$

and

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$$\cos(\theta_V) = \frac{V_r}{(V_r^2 + V_i^2)^{0.5}}$$

5

$$\sin(\theta_V) = \frac{V_i}{(V_r^2 + V_i^2)^{0.5}}$$

$$\cos(\theta_I) = \frac{I_r}{(I_r^2 + I_i^2)^{0.5}}$$

10

$$\sin(\theta_I) = \frac{I_i}{(I_r^2 + I_i^2)^{0.5}}$$

15

then by substitution

$$\text{instantaneous power factor} = (Vr*Ir + Vi*Ii)/((Vr^2 + Vi^2)*(Ir^2 + Ii^2))^{0.5}$$

This equation is the form used by the processor 80 and the algorithm

20   140 to calculate a value of instantaneous power factor. This equation uses the

levels of the voltages and currents and does not directly use trigonometric

functions or phase angles. No conversion between wye and delta

configurations is needed.

To calculate a value of true three-phase power factor, the processor 80

25   samples and calculates multiple instances of values of instantaneous power

factor at a pre-determined sampling rate over a pre-determined time interval

(such as about but preferably not equal to a line cycle) of the three-phase

power system. It is preferable that sampling rate not be equal to a line cycle so

that sample locations in a line cycle are distributed in relation to a line cycle

30   period but it is also preferable that the interval over which the samples are

averaged is an exact multiple of the line cycles both for 50 Hz and 60 Hz.

This provides a representative sampling of the instantaneous power factor. In

one embodiment of the invention, this pre-determined sampling rate is every

2.5 msec. A line cycle is typically 20 msec or 16.67 msec corresponding to 50 Hz or 60 Hz source power respectively. The algorithm 140 then averages these values of instantaneous power factor to obtain a value of true three-phase power factor.

5   This value of true three-phase power factor represents the effective power factor of the load the power is being sourced to and has improved insensitivity to any imbalances of the source, line, or load. This method of calculating power factor is independent of source and load wye and delta configurations. This method is also independent of the configuration in which

10   the voltage and current levels are measured. For example, they may be measured inside or outside a delta motor with the same results. Time intensive sampling of the voltage and current levels is avoided with this method. A processor with a fast clock and higher cost can, therefore, be avoided. These calculations of power factor are highly accurate to give the customer a true

15   sense of the operating point of the system. These calculations of power factor can be used in time critical functions such as detection of momentary power loss (MPL) conditions and detection of surge conditions. With this implementation, expensive instrument grade power factor meters can be avoided. The same simple components and processor capability that are used

20   for normal operation of, for example, a chiller motor can be used for determining power factor with this method.

Figure 4 illustrates how the processor 80 uses values of instantaneous power factor to detect a momentary loss of power (MPL) condition using the MPL algorithm 150. The three-phase power system is continuously monitored

25   for an MPL condition. In step 250 of the MPL algorithm 150, the algorithm 140 is called to calculate consecutive instances of values of instantaneous three-phase power factor at a pre-determined sampling rate. In one

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embodiment of the invention, this sampling rate is every 7.5 msec. In step 260 the values of instantaneous three-phase power factor are checked to determine if they are positive (numerically greater than zero). As long as the instantaneous power factors are positive, an MPL condition does not exist. In step 270, the algorithm 150 checks to see if the last six consecutive values of instantaneous three-phase power factors have been non-positive (numerically less than or equal to zero). If this is the case, then an MPL condition is detected as shown in step 280. The processor 80 then commands the motor contactors 130 to disconnect power from the motor 60. This will prevent damage from occurring to the motor 60 and/or load 70 due to the MPL condition. A pre-determined time interval elapses before the processor 80 attempts to re-connect source power to the motor 60.

Using power factor to determine an MPL condition is beneficial because the power factor represents the true state of the motor 60 at any point in time. This method is very responsive to power line anomalies, allowing the controls to obtain accurate information quickly. This method is also insensitive to DC offsets and non-symmetry of reclosure currents. It is also less sensitive to voltage and current unbalance conditions.

While the invention is described in connection with one embodiment, it will be understood that the invention is not limited to that one embodiment. On the contrary, the invention covers all alternatives, modifications, and equivalents within the spirit and scope of the appended claims.

For example, some possible alternatives might include the following described below. The voltage and current levels may not be sampled at the same time. The up to six inputs could be sampled and stored one at a time with a standard analog-to-digital converter that is subsequently read by the processor, or sampled in some other combination.

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As another alternative, the three-phase power system may be monitored non-continuously for an MPL condition instead of continuously. For example, monitoring for an MPL condition may be initiated only when some other condition is detected first, such as, for example, a surge condition.

5   As a further alternative, the various algorithms may be combined in various ways or separated in various ways depending on the exact software implementation desired.